

The effect of metallicity on the delay-time distribution of type Ia supernova

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(Received 2000 December 31; accepted 2001 January 1)

Abstract

Measuring the delay-time distribution (DTD) of type Ia supernova (SNe Ia) is an important way to constrain the progenitor nature of SNe Ia. Recently, Strolger et al. (2010) obtained a very delayed DTD, which is much different from other measurements. They suggested that metallicity could be the origin of their delayed DTD. In this paper, we show the effect of metallicity on the DTD of SNe Ia from single-degenerate models (including WD + MS and WD + RG channels). Via a binary population synthesis approach, we find that the DTD from a low metallicity population is significantly delayed compared with that from a high metallicity one. In addition, we also find that a substantial fraction of SNe Ia have a delay time shorter than 1 Gyr, and the fraction of SNe Ia with short delay times increases with metallicity, i.e. about 35% for $Z=0.001$, while more than 70% for $Z=0.02$. These results would help to qualitatively explain the result of Strolger et al. (2010). Furthermore, we noticed that the contribution of WD + RG channel from the low metallicity population is higher than that from the high metallicity one. However, we can not quantitatively obtain a DTD consistent with the results of Strolger et al. (2010) by changing metallicity. As a consequence, metallicity may partly contribute to the DTD of SNe Ia and should therefore be checked carefully when one derives the DTD of SNe Ia from observations.

Key words: stars: binaries: general—stars: supernovae: general—stars: white dwarfs

1. Introduction

Although Type Ia supernovae (SNe Ia) are very important in cosmology (Riess et al. 1998; Perlmutter et al. 1999), the exact nature of their progenitors is still unclear (Hillebrandt & Niemeyer 2000; Leibundgut 2000; Parthasarathy et al. 2007). There is a consensus that SNe Ia result from the thermonuclear explosion of a carbon-oxygen white dwarf (CO WD) in a binary system (Hoyle & Fowler 1960). According to the nature of the companions of the mass accreting WDs, two basic scenarios for the progenitors of SN Ia have been discussed over the last three decades. One is the single degenerate (SD) model (Whelan & Iben 1973; Nomoto, Thielemann & Yokoi 1984), i.e. the companion is a main-sequence or a slightly

evolved star (WD+MS), or a red giant star (WD+RG) or a helium star (WD + He star) (Li & van den Heuvel 1997; Hachisu et al. 1999a; Langer et al. 2000; Han & Podsiadlowski 2004; Chen & Li 2007; Meng, Chen & Han 2009; Lü et al. 2009; Wang et al. 2009; Wang, Li & Han 2010). The other is the double degenerate (DD) model, i.e. the companion is another WD (Iben & Tutukov 1984; Webbink 1984). Measuring the delay-time distribution (DTD, delay time is the elapsed time between primordial system formation and explosion as a SN Ia event) is a very important way to distinguish between the different progenitor systems. Recently, using the high-redshift SNe Ia sample ($0.2 < z < 1.8$) from the Hubble Space Telescope ACS imaging of the GOODS North and South fields, Strolger et al. (2010) showed a significantly delayed DTD that is confined to 3–4 Gyr, which is difficult to resolve with any intrinsic DTD. This result confirmed their previous findings (Strolger et al. 2004). But, they also noticed that this result is mainly motivated by the decline in the number of SNe Ia at $z > 1.2$. Their sub-samples with low redshift ($z < 1.2$) showed plausible DTDs dominated by SNe Ia with short delay times. The difference between their low- z and high- z results may be partly ex-

* We are grateful to Dr. Richard Pokorný for improving the English language of the original manuscript and thanks the anonymous referee for his/her constructive suggestions which make the manuscript more complete. This work was partly supported by Natural Science Foundation of China under grant nos. 10963001 and 11003003, the Project of Science and Technology from the Ministry of Education (211102), and the Project of the Fundamental and Frontier Research of Henan Province under grant no. 102300410223.

plained by the fact that a substantial fraction of $z > 1.2$ supernova may be obscured by dust. However, the DTD derived by Strolger et al. (2010) may be dominated by systematic errors, in particular due to uncertainties in the star formation history (SFH, Förster et al. 2006). The inferred delay time is strongly dependent on the peak in the assumed SFH and none of the popular progenitor models under consideration can be ruled out with any significant degree of confidence (see also Oda et al. 2008 and Valiante et al. 2009).

Moreover, the results of Strolger et al. (2010) are inconsistent with many low and moderate redshift measurements, which showed that most SNe Ia have delay times between 0.3 and 2 Gyr (Schawinski 2009), and there are also SNe Ia with very long delay times (older than 10 Gyr inferred from SNe Ia in elliptical galaxies in the local universe, Mannucci et al. 2005) or extremely short delay times (shorter than 0.1-0.3 Gyr, Mannucci et al. 2006; Schawinski 2009; Raskin 2009). Based on some observations, i.e. the strong enhancement of the SN Ia birthrate in radio-loud early-type galaxies, the strong dependence of the SN Ia birthrate on the colors of the host galaxies, and the evolution of the SN Ia birthrate with redshift (Della Valle et al. 2005; Mannucci et al. 2005; Strolger et al. 2004), Mannucci et al. (2006) suggested a bimodal DTD, in which some of the SNe Ia explode soon after starburst with a delay time less than 0.1-0.5 Gyr ('prompt' SNe Ia, Schawinski 2009; Raskin 2009), while the rest have a much wider distribution with a delay time of about 3 Gyr ('tardy' SNe Ia). In theory, the bimodal DTD may be constructed from detailed binary population synthesis (Meng & Yang 2010a). However, the excess of SNe Ia in radio galaxies is the only one observation that strongly indicates an extremely large amount of the prompt population and hence is distinct from the longer delay time population (see Mannucci et al. 2006), **but** this excess is not supported by a more recent observation (Graham et al. 2010). By comparing with host galaxy color, some authors proposed a simple two-component model, A+B model, which may be a variation of the bimodal DTD. (Scannapieco & Bildsten 2005; Sullivan et al. 2006; Brandt et al. 2010). Recently, more and more observational evidence showed that the DTD of SNe Ia follows the power-law form of t^{-1} which is much different from the results of Strolger et al. (2010). The power-law form is even different from the bimodal model or the A+B model, which might indicate that the simple two-component model is an insufficient description for observational data. (Totani et al. 2008; Maoz 2010; Maoz et al. 2010; Maoz et al. 2011). Even via the same method as Strolger et al. (2010), i.e. comparison between cosmic SFR evolution and SN Ia rate evolution, a t^{-1} DTD was also found to be in nice agreement with observed data (Graur et al. 2011). The DTD derived by Strolger et al. (2010) is well confined to 3-4 Gyr which is strongly inconsistent with those DTDs mentioned above, and only a small fraction belong to the "prompt"¹ SNe Ia

population, i.e. smaller than 10%. However, some low-redshift samples show the existence of prompt SNe Ia at a high confidence level, and the birth rate of the prompt component is much higher than that of the tardy SNe Ia (Aubourg et al. 2008; Maoz et al. 2011). Theoretically, short delay SNe Ia may also be produced by a WD + helium star and WD + MS channel (Wang et al. 2009; Meng & Yang 2010a).

Whatever, Strolger et al. (2010) suggested that the effect of metallicity could be one possible resolution for disagreement between their discovery and low/moderate results. In this paper, we want to check whether changing the metallicity can create DTDs consistent with the results of Strolger et al. (2010), in the framework of the single-degenerate scenario.

In section 2, we simply describe our method, and present the calculation results in section 3. In section 4, we show discussions and our main conclusions.

2. METHOD

Recently, Meng & Yang (2010a) constructed a comprehensive single degenerate progenitor model for SNe Ia. In this model, the mass-stripping effect of optically thick wind (Hachisu et al. 1996) and the effect of a thermally instable disk were included (Hachisu et al. 2008; Xu & Li 2009). The prescription of Hachisu et al. (1999a) on WDs accreting hydrogen-rich material from their companions was applied to calculate the WD mass growth. The optically thick wind and the material stripped-off by the wind were assumed to take away the specific angular momentum of the WD and its companion, respectively. In Meng & Yang (2010a), both WD + MS channel and WD + RG channel are considered, i.e. Roche lobe overflow (RLOF) begins at MS or RG stage. The Galactic birth rate of SNe Ia derived from that model is comparable with that from observations. In addition, this model may even explain some supernovae with low hydrogen mass in their explosion ejecta (Meng & Yang 2010b). Meng & Yang (2010a) calculated more than 1600 WD close binary evolutions and showed the initial parameter space leading to SNe Ia in an orbital period - secondary mass ($\log P_1, M_2^1$) plane, and these results may be conveniently used in a binary population synthesis code for obtaining the DTD of SNe Ia.

The delay time of a SN Ia from the SD model is mainly determined by the stellar evolutionary timescale of the secondary, and thus the secondary mass. That is to say that the DTD of SNe Ia is a function of the location of the parameter space in the ($\log P_1, M_2^1$) plane. However, this location is directly affected by metallicity. For a system with given initial WD mass and orbital period, the initial mass of the companion leading to SNe Ia increases with metallicity, i.e. the upper boundary and lower boundary of the companion mass move to lower values with the decrease of metallicity (see the figure 4 in Meng, Chen & Han 2009). Thus, the DTD of SNe Ia are affected by

¹ The delay time of the prompt SNe Ia in Strolger et al. (2010) is still much delayed compared with that suggested by Mannucci

et al. (2006)

metallicity via companion mass. Between the two boundaries of the companion mass for SNe Ia, the lower boundary dominates the longer delay time of SNe Ia. The low boundary is mainly determined by the condition that the mass transfer rate between a CO WD and its companion is higher than a critical value which is the lowest accretion rate of a CO WD avoiding violent nova explosion, while the upper boundaries are mainly determined by dynamically unstable mass transfer and the strong hydrogen-shell flash. The mass transfer rate for a given binary system is closely related to metallicity, which is due to the correlation between stellar structure and metallicity (Umeda et al. 1999a; Chen & Tout 2007). Generally, the time-scale for mass transfer is the thermal time-scale, which increases with metallicity. This leads to a higher mass-transfer rate for a low metallicity system (Langer et al. 2000). So, low-mass companions with low metallicity are thus more likely to fulfill the constraint for mass transfer than those with high metallicity. A WD + MS system with a low metallicity is therefore more likely to be the progenitor of a SN Ia (see also Meng, Chen & Han 2009). On the other hand, a high mass-transfer rate means that a binary system with the same initial parameters but at low metallicity will fulfill the condition of dynamical instability more possible. Even though the mass transfer for the system is dynamically stable, the mass-transfer rate could be so high that most of the transferred material is lost from the system by the optically thick wind, and at the same time, a large amount of hydrogen-rich material stripped off by the wind is lost from the companion envelope. The mass-transfer rate then sharply decreases to less than the critical value for avoiding the strong hydrogen-shell flash after mass-ratio inversion. As a consequence, the initial parameter space for SNe Ia moves to a lower companion mass with the decrease of metallicity (Meng, Chen & Han 2009). For example, for a system with given initial WD mass and initial orbital period, the companion mass for $Z = 0.001$ is lower than that of $Z = 0.02$ by about $0.4 M_{\odot}$ (see also Chen & Li 2009). In this paper, we do not calculate binary evolution for low metallicity, instead we move the parameter space for SNe Ia of $Z = 0.02$ given by Meng & Yang (2010a) to a lower companion mass by $0.4 M_{\odot}$ and assume rather arbitrarily that the parameter space with a low companion mass is equivalent to that for $Z = 0.001$. To clarify what we did, we use the case of $M_{\text{WD}}^i = 1.00 M_{\odot}$ as an example (see figure 1)². Since we only want to check whether the metallicity has an ability to create a DTD matching with the discovery of Strolger et al. (2010), this simple assumption is not unreasonable (see discussion in section 4.3).

To obtain the DTD of $Z = 0.001$, we have performed a

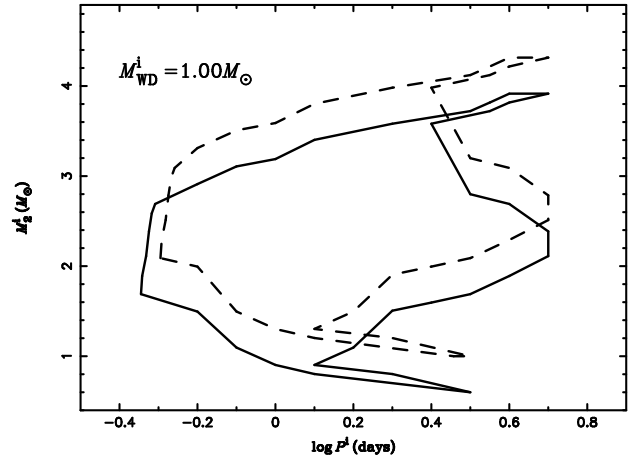


Fig. 1. The contours shown by solid and dashed lines are the parameter space for SNe Ia with $Z = 0.001$ and $Z = 0.02$, respectively, where the initial WD mass is $1.00 M_{\odot}$.

series detailed Monte Carlo simulations via Hurley’s rapid binary evolution code (Hurley et al. 2000; Hurley et al. 2002). In the simulations, if a binary system evolves to a WD + MS or WD + RG stage, and the system is located in the $(\log P^i, M_2^i)$ plane for SNe Ia at the onset of RLOF, we assume that a SN Ia is produced. In the simulations, we follow the evolution of 10^7 sample binaries. The evolutionary channel is described in Meng & Yang (2010a). As in Meng & Yang (2010a), we adopted the following input for the simulations. (1) A single starburst is assumed, i.e. $10^{11} M_{\odot}$ in stars are produced at one time. (2) The initial mass function (IMF) of Miller & Scalo (1979) is adopted. (3) The mass-ratio distribution is taken to be constant. (4) The distribution of separations is taken to be constant in $\log a$ for wide binaries, where a is the orbital separation. (5) A circular orbit is assumed for all binaries. (6) The common envelope (CE) ejection efficiency α_{CE} , which denotes the fraction of the released orbital energy used to eject the CE, is set to 1.0 or 3.0. (See Meng & Yang (2010a) for details).

3. RESULT

In figure 2, we show the evolution of the birthrates of SNe Ia for a single starburst for different α_{CE} and different metallicities. We can see from the figure that whatever the α_{CE} , the DTDs of $Z = 0.001$ are significantly delayed compared with those of $Z = 0.02$. For $Z = 0.02$, SNe Ia mainly occur between 0.2 and 2 Gyr with a mean value of 0.89 Gyr after the burst, while they occur between 0.3 and 3.5 Gyr with a mean value of 1.94 Gyr for $Z = 0.001$. This is mainly derived from the low companion mass for low metallicity. As stated in Han & Podsiadlowski (2004) and Meng & Yang (2010a), we found that a high α_{CE} leads to a systematically later explosion time for $Z = 0.001$, because a high α_{CE} leads to wider WD binaries, and as a consequence, it takes a longer time for the secondary to evolve to fill its Roche lobe. As noticed by Meng, Chen & Han (2009), the peak value of the DTD for low metallic-

² In this paper, we do not directly use the results in Meng, Chen & Han (2009) because the calculations in the paper is not as complete as in Meng & Yang (2010a), i.e. they did not consider the WD + RG channel which is the dominant one for old SNe Ia, and did not incorporate some special effects such as the mass-stripping effect of optically thick wind and the effect of a thermally unstable disk which could be very important for SNe Ia.

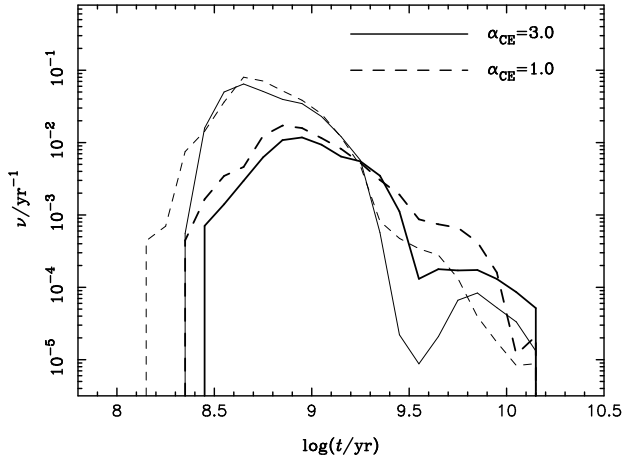


Fig. 2. Evolution of the birthrates of SNe Ia for a single starburst of $10^{11} M_{\odot}$ for different α_{CE} (solid lines: $\alpha_{CE} = 3.0$; dashed lines: $\alpha_{CE} = 1.0$) and different metallicities. The thick lines are the results for $Z = 0.001$ in this paper and the thin ones are for $Z = 0.02$ from Meng & Yang (2010a).

ity is lower than that for high metallicity and the WD + MS channel is the dominant channel for the peak value. However, the contribution of WD + RG channel to SNe Ia for $Z = 0.001$ is higher than that for $Z = 0.02$, i.e. 1%-2% for $Z = 0.02$, but 8.6%-16% for $Z = 0.001$. Actually, Meng, Chen & Han (2009) noticed that the WD + RG channel may be more common for low metallicity (see footnote 1 in Meng, Chen & Han 2009).

We also checked the fraction of SNe Ia with short delay times and found that a substantial fraction of SNe Ia have a delay time shorter than 1 Gyr and the fraction of SNe Ia with short delay times increases with metallicity, i.e. about 35% for $Z = 0.001$, while more than 70% for $Z = 0.02$.

4. DISCUSSIONS AND CONCLUSIONS

4.1. comparison with observations

Measuring the DTD of SNe Ia is an important way to constrain the nature of the progenitor of SNe Ia. Recently, Strolger et al. (2010) used data from the Hubble space telescope to confirm their previous results that the data are largely inconsistent with progenitor scenarios with short delay time, which is difficult to explain with any intrinsic DTD. Strolger et al. (2010) suggested a possible resolution for their results, i.e. environment such as metallicity may affect the progenitor mechanism efficiently, especially in the early universe. Our results in this paper seem to support this suggestion because we found that low metallicity may significantly delay the DTD of SNe Ia. If the result obtained by Strolger et al. (2010) shows the real nature of the DTD of SNe Ia, metallicity could be an indispensable factor which must be considered when studying the progenitors of SNe Ia. However, for a high- z SNe Ia sample as used by Strolger et al. (2010), whether metallicity works as significantly as suggested in this paper should be checked carefully since optically thick wind could not

work, and thus SNe Ia could not occur in a low-metallicity environment (Kobayashi et al. 1998). Furthermore, the evolution of metallicity with redshift should be considered carefully (see next section), since the results of Strolger et al. (2010) depend strongly on the SNe Ia sample with $z > 1.2$. The DTD derived from the sub-sample with $z < 1$ is consistent with results from low-redshift supernova samples, which are better reproduced by our model. Thus, the properties of SNe Ia with $z > 1.2$ (their progenitors may form at a red shift as large as 3-4) are interesting.

Recently, By comparing a theoretical DTD and an observational one from Totani et al. (2008), Mennekens et al. (2010) claimed that the DTD from the single degenerate model is incompatible with observations, which is mainly derived from a lower birth rate of SNe Ia at long delay time, especially at a time longer than 8 Gyr. Metallicity may improve the situation of the SD model since a low metallicity may increase the birth rate of SNe Ia from WD + RG channel as suggested in this paper and after all, the DTD derived from the SD model by Meng & Yang (2010a) is not incompatible with observations.

4.2. the evolution of DTD with redshift

Generally, the mean value of metallicity decreases slowly with redshift. Based on the results in this paper, the mean delay time of SNe Ia could thus increase with redshift. However, the evolution of metallicity is not a simple, monotonic function of redshift. Metallicity shows a significant scatter at all redshifts and the scatter increases with redshift (Nagamine et al. 2001). At $z \simeq 3-4$, the mean value of metallicity is close to 0.005. According to the results here, the progenitors of SNe Ia formed at this redshift interval would then explode at an interval of $z \simeq 1.5-2.5$, and the delay time could be shorter than 2.75 Gyr. Even at $z = 5$, the mean metallicity is 0.004. The progenitor stars formed at such high redshifts contribute to SNe Ia exploding at $z > 2$, which is beyond the scope of SNe Ia sample used by Strolger et al. (2010). Stars formed at $z \simeq 2$ usually have a metallicity lower than 0.02, i.e. the metallicity spreads from $0.01-1Z_{\odot}$ and has a mean value of $\sim 0.6Z_{\odot}$, where Z_{\odot} is solar metallicity (Nagamine et al. 2001). Thus, the progenitors formed at $z \simeq 2$ could not contribute to SNe Ia with long delay times at $z \simeq 1-2$, and the delay time at this redshift interval should be shorter than 2 Gyr. For stars formed at $z \leq 1.5$, the distribution of metallicities is rather uniform, i.e. close to Z_{\odot} , and these stars mainly contribute to SNe Ia exploding at $z \leq 1$, which means that SNe Ia at $z \leq 1$ usually have a delay time shorter than 2 Gyr. So, there is no time at which the average metallicity of $Z < 0.001$ contributes to the high-redshift sample of Strolger et al. (2010). Even if it were, our model would predict $\sim 35\%$ of the SNe Ia to be “prompt”, which is inconsistent with the results of Strolger et al. (2010). However, as noticed by Nagamine et al. (2001), the spread of metallicity gradually increases toward high redshift. It takes $0.01-1.0Z_{\odot}$

at $z = 2$, but $10^{-6} - 3.0Z_{\odot}^3$ at $z > 3$. Thus, there are still a few progenitor stars formed at $z > 3$ which could contribute to SNe Ia with long delay times at $z \simeq 1 - 2$. So, although metallicity has no ability to create a DTD matching the discovery of Strolger et al. (2010), it still partly contributes to the discovery.

The WD + MS channel is the dominant one for SNe Ia, and the discussion above is mainly based on this channel. Although the contribution is small (1% - 16%, see section 3), the WD + RG channel contributes to SNe Ia with very long delay times, i.e. longer than 3.5 Gyr. So the SNe Ia from this channel could only be discovered at $z < 2$, and the progenitor stars formed at $z < 4$ could contribute to SNe Ia at $z < 1$.

4.3. uncertainties

Obviously, there exist many uncertainties for our discussions in this paper. Firstly, we did not calculate the binary evolution with low metallicity, i.e. we did not obtain the appropriate parameter space for SNe Ia with low metallicity. Fortunately, some works have referred to this problem, i.e. the parameter space for SNe Ia moves to lower secondary mass with the decrease of metallicity, and then a low metallicity leads to a longer delay time (Meng, Chen & Han 2009; Chen & Li 2009). So, as the effect of metallicity on the delay time of SNe Ia, we seem not to obtain a new result. But, since our purpose is to check whether changing metallicity can create DTDs consistent with the results of Strolger et al. (2010), our work is still meaningful. Then, the following question is whether $0.4 M_{\odot}$ used here is reasonable although this value is obtained from detailed binary evolution calculation. Actually, the lower boundary of the parameter space for SNe Ia with $Z = 0.001$ is lower than $0.8 M_{\odot}$ when we move the parameter space for SNe Ia of $Z = 0.02$ to a lower companion mass by $0.4 M_{\odot}$, which means that we obtained an upper limit of the effect of metallicity on the delay time of SNe Ia. In addition, a low metallicity reduces the area of parameter space for SNe Ia (Nomoto et al. 1999; Meng, Chen & Han 2009; Chen & Li 2009). However, the area mainly affects the birth rate of SNe Ia, not delay time, i.e. the birth rate of $Z = 0.001$ obtained here could be taken as an upper limit, but the delay time here is still valid. So, the conclusion that metallicity has no ability to interpret the observation of Strolger et al. (2010) is reasonable.

Secondly, in the calculation of Meng & Yang (2010a), the optically thick wind is assumed (Hachisu et al. 1996), which critically depends on the opacity applied, i.e. it is likely that the wind does not work when $Z < 0.002$ and then SNe Ia should not be observed in metal-poor environments (Kobayashi et al. 1998). However, this prediction was not upheld by some observations (Prieto et al. 2008; Badenes et al. 2009; Khan et al. 2010). To try to avoid arguments, we assume that the wind still works when $Z = 0.001$ (slightly lower than the metallicity limit of $Z = 0.002$, see also Nomoto et al. 1999), and then the de-

lay time obtained here should be taken as an upper limit. Since the upper limit of delay time can not match with the DTD of Strolger et al. (2010), our conclusion is still hold no matter which value of metallicity we choose.

Thirdly, the single-degenerate model in Meng & Yang (2010a) contains numerous assumptions, which may not be universally accepted. For example, the mass-stripping effect of the optically thick wind and the effect of the thermally instable disk were included (Hachisu et al. 2008; Xu & Li 2009). The mass stripping effect mainly affects the birth rate of SNe Ia, i.e. the birth rate may reduce significantly if the effect is not include (see Wang, Li & Han 2010). The effect of the thermally instable disk affects not only the birth rate, but also the delay time. If this effect were not include, the birth rate and the delay time would decrease significantly, which might lead to a DTD that is also not consistent with the observation of Strolger et al. (2010).

Finally, please keep in mind that there is an implicit assumption in this paper that the assumptions used in Meng & Yang (2010a) is not affected by metallicity. This assumption is rather arbitrary since great efforts are necessary to support it. Fortunately, some previous studies showed that the influence of metallicity on the assumptions used in SD model could be neglected. For example, the critical accretion rate and the structure of WDs are almost not affected by metallicity (Meng et al. 2006; Umeda et al. 1999a; Umeda et al. 1999b). So, our assumption here might not be a serious problem.

In summary, this paper fails its stated goal: to create a DTD consistent with the measurement of Strolger et al. (2010) by changing metallicity based on a SD scenario. Metallicity may only partly resolve the long delay-time results of Strolger et al. (2010). However, when using the delay time derived from observations to constrain the progenitors of SNe Ia, metallicity should be carefully checked.

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³ The existence of an optically thick wind is in doubt for very low metallicity (Kobayashi et al. 1998).

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